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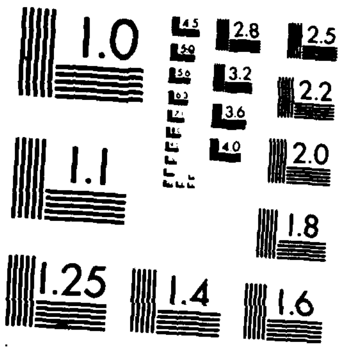

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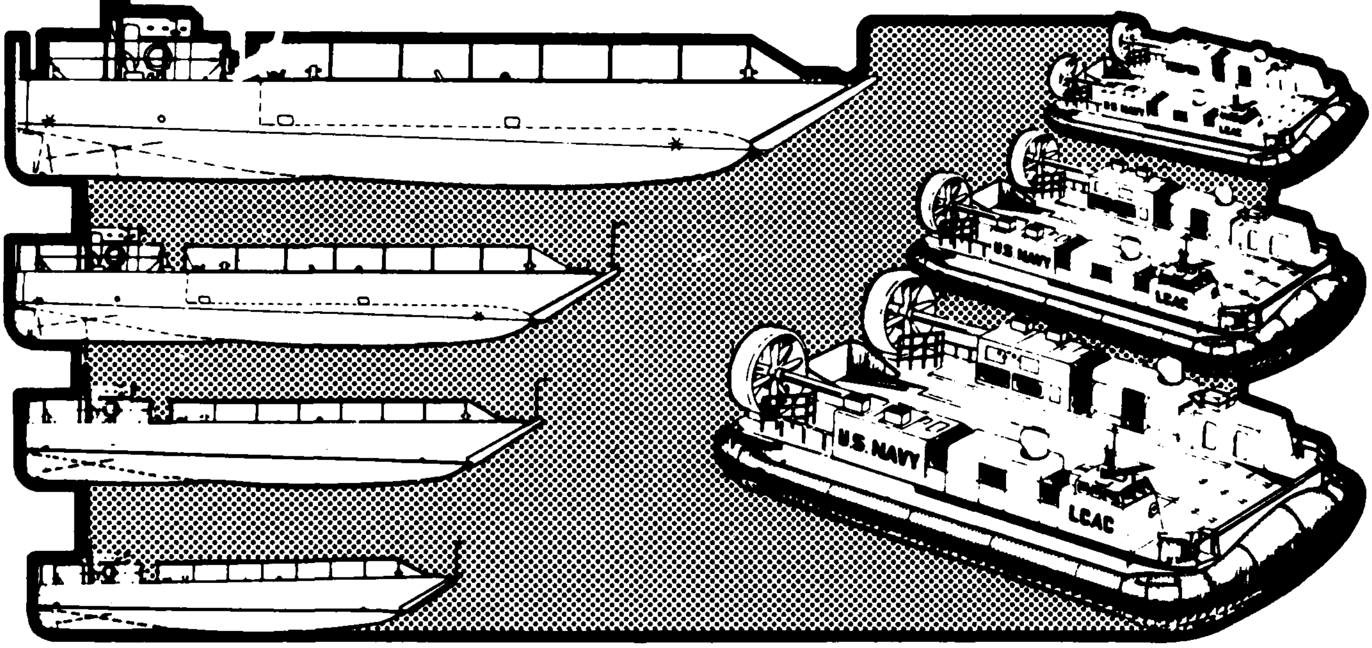

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FIBER OPTICS

by: J. Davis

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FIBER OPTICS

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April 4, 1986

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FIBER OPTICS

BY: JIM DAVIS

NOTE: THE TITLE AND CONTENT OF THIS PAPER HAVE BEEN MODIFIED FROM THAT ORIGINALLY PLANNED DUE TO RECENT CHANGES IN FIBER OPTICS SECURITY CLASSIFICATION GUIDELINES.

ABSTRACT

Fiber optics is a rapidly developing technology that is being used in the design of ships and ship systems. This paper includes a brief overview of the history of fiber optics, the characteristics of optical fiber, the technology of fiber optics, and commercial applications for fiber optics.

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1.0 INTRODUCTION

Fiber optics is one of the most promising of the new technologies being used by engineers and designers to improve the efficiency and effectiveness of new ships and ship systems. The basis of this new technology is the optical fiber, a thin, flexible glass or plastic waveguide through which light is transmitted. The most common use of optical fiber is as a transmission link in communication systems. The fibers are also finding increasing use in medical endoscopy, industrial inspection, and as highly sensitive sensors.

2.0 CHARACTERISTICS OF OPTICAL FIBER

Optical fibers have unique characteristics and capabilities that are extremely useful. First, the data-carrying capacity of the hair-thin fibers is thousands of times greater than that of coaxial cable or twisted-pair wire.

Second, optical fibers are essentially immune to electromagnetic interference from lightning and radio or radar transmitters, and they can survive electromagnetic pulses from nuclear explosions.

Third, fiber cables can be made very secure. In the military, we spend a lot of time and money ensuring that our classified data links are secure. A standard copper cable can be tapped by wrapping a coil of wire around it. To tap an optical cable, you must cut into the cladding and remove some of the light, thus damaging the cable and causing an optical power loss. Both are easy to detect.

Fourth, because optical fibers are made of either polymers or glass, they do not conduct electricity. Because there is no electricity, and therefore no danger that a short circuit will cause sparks or high temperatures, we can safely use fiber cables in highly explosive environments, such as fuel and munition storage areas. In addition, the nonconductive properties of fiber optic cables allow the isolation of the optical transmitters and receivers in the system. The isolation eliminates the need for a common electrical ground loop and thus eliminates line-balancing problems. The isolation also decreases the noise in the electronic part of the system.

Fifth, glass fibers are rugged. Fibers are being deployed from airplanes and missiles. They are being proof tested at tensile strengths of more than 400,000 psi (2.7 gigapascal).

Sixth, the small diameter of fiber optic cable offers substantial size and weight advantages over metallic cable of equivalent bandwidths.

Seventh, in many commercial applications, the total system cost for a fiber optic design has been appreciably lower than for a wire system.

3.0 A REVIEW OF THE TECHNOLOGY

Fiber optics can be defined as "The branch of optical technology concerned with the transmission of radiant power through fibers made of transparent materials such as glass, fused silica, or plastic."[1]

The radiant power, or light, used in fiber optic systems is electromagnetic energy that is several orders of magnitude higher in frequency than are radio waves. In a description of light waves, it is usually more convenient to use wavelength than freqency. For instance, fiber optic systems are usually described as being designed to operate somewhere in the 750- to 1600-nm region.

Light travels at the speed of light, 186,282 miles per second (300,000 km/s), in free space. It travels more slowly in other media, and different wavelengths travel at different speeds in the same medium. When light passes from one medium to another, it changes speed, which causes a deflection of light called "refraction." The ratio of the velocity of light in free space to its velocity in a specific medium is called the "index of refraction." The higher the refractive index of a medium, the more slowly light will travel in it.

$$\text{REFRACTIVE INDEX } n \text{ OF A MEDIUM} = \frac{\text{SPEED OF LIGHT IN A VACUUM}}{\text{SPEED OF LIGHT IN THE MEDIUM}}$$

Light is propagated in an optical fiber by total internal reflection. According to Snell's law of refraction, a light beam directed from a medium with a high index of refraction to a medium with a lower index of refraction will be totally reflected if the beam's angle of incidence is greater than the critical angle. See Figure 1. In an optical fiber, the high-index material is called the "core" and the lower-index material is called the "cladding."[2]

The exact characteristics of light propagation along an optical fiber depend on the size of the fiber, what the fiber is made of, how it is made, and the nature of the injected light. Maxwell's electromagnetic equations show that light does not travel randomly through a fiber; it is channeled into modes. In its simplest terms, a mode can be defined as a possible path for a light ray traveling down a fiber.

Three major types of optical fiber are commonly used: multimode step-index, multimode graded index, and single-mode step-index. Structurally, they differ in their refractive-index profiles and in their cross-sectional dimensions. See Figure 2.

Multimode step-index is the oldest type of optical fiber and has the lowest bandwidth. The core of this type of fiber is surrounded by a cladding with a lower refractive index than that of the core. This discontinuity, or "step," in the refractive

index, creates a boundary between the core and the cladding. Light rays sent through the fiber take multiple paths or modes as shown in Figure 3. Because light reflects differently for different modes, some rays follow longer paths than others do. The lowest-order mode, the axial ray traveling down the center of the fiber without reflecting, arrives at the other end of the fiber first. The higher-order modes that strike the core-to-cladding interface follow longer paths. This causes the light pulses to spread out as they travel along the fiber. This phenomenon is called "modal dispersion" and results in a reduction in the potential bandwidth of the fiber. The problem gets worse as the fiber core increases in diameter.

Multimode step-index fibers are used in short-distance, low-bandwidth systems. Multimode fiber is the easiest type to connect or splice, because the large core (50-1000 micrometers) is easy to align.

Multimode graded-index fibers guide light by using refraction instead of reflection. The core of a graded-index fiber is a series of concentric rings, each with a lower refractive index than that of the adjacent inner ring. Because light travels faster in a lower-index medium, a ray will increase in speed as it travels further from the axis. Thus the high-order modes will have a faster average velocity than will the low-order modes, and all modes will tend to arrive at any point at nearly the same time. Modal dispersion in graded-index fiber can be less than 1 ns/km. The bandwidth can exceed 1 GHz-km.

The three primary types of multimode fiber are all-glass, plastic-clad silica (PCS), and all-plastic. All-glass fiber generally has an attenuation level between 0.2 and 10 dB/km, a numerical aperture (light input acceptance angle) of 0.2, core diameters of 50 to 70 micrometers, outer diameters of 125 micrometers, and bandwidths up to 1 GHz-km. They may be either step-index or graded-index.

PCS fiber has bandwidths from under 1 MHz to about 25 MHz, and attenuation is higher than that of all-glass fiber. Because of the larger diameter (150- to 300-micrometer core, 400-micrometer outside diameter), PCS fiber is more easily connected than are all-glass fibers.

Plastic fiber has attenuation ranging from 30 to 400 dB/km and is suitable for communication links of up to about 100 meters. They are rugged, have a high numerical aperture (about 0.5) and a large core (350-1000 micrometers).[2]

Single-mode step-index fibers have core diameters on the order of 2 to 10 micrometers. The small core limits the propagated light to a single mode or path. Because the light cannot vary in either the path it takes or the length of the path, modal dispersion is eliminated. Single-mode fiber has an incredible

bandwidth of more than 50 GHz-km. Single-mode fiber has advantages in size, performance, economy, reliability, and design flexibility over multimode fiber. However, because of the small size of the core, splicing and launching light into it requires more precision. Single-mode fiber is the fiber of choice for high-speed systems and for those applications that have a long distance between the transmitter and receiver or transmitter and repeater. Single-mode fiber is also beginning to be used in local area networks (LAN).

A simple fiber optic system consists of a transmitter, a fiber, a receiver, and connectors to join these components. Most fiber optic systems transmit digital data that consist of a series of on-and-off light pulses.

The transmitter has the task of converting the input signal, which is normally electrical, into a packet of light, or photon. The light signals from the transmitter are conveyed as a series of pulses; therefore, the light source must not only be able to emit a bright, highly directional signal, but also be able to be turned on and off very quickly. The more rapid the modulation of the light source is, the more information that can be conveyed in a given time.

There are two types of semiconductor light sources in use today for fiber optic transmission: light-emitting diodes and lasers. Light-emitting diodes (LEDs) are used widely in transmission systems over short distances. LEDs radiate with an optical power proportional to the driving current, and have a wide emission angle. The LEDs used in fiber optic systems are refined versions of what is found in today's pocket calculators. Although they are not as powerful as lasers, they are much less expensive. Most use gallium arsenide (GaAs) to generate the light source.

The laser, or injection laser diode (ILD), is the most promising light source for fiber optic transmission. The laser, well suited for digital fiber optic transmissions, has numerous advantages over the LED. Laser diodes are about the size of a grain of salt and are made of gallium arsenide doped with aluminum (GaAlAs). The light from a laser is much more directional than that from an LED, resulting in less scattering.

Getting the light from the laser or LED into the core of the optical fiber requires precise work because the sizes involved are so small. Usually, a short length of fiber, called a "pigtail," is epoxied to the light source. This must be done under a microscope to ensure proper alignment. The pigtails are about one-meter long and are permanently attached to the light source. The other end of the pigtail fiber is often terminated with an optical connector.

Optical connectors must provide precise alignment, mechanical integrity after repeated coupling and uncoupling, a flat, optically clean surface perpendicular to the fiber centerline, and separation of fiber ends to prevent scratching. The connectors must also be rugged enough to withstand rough handling, vibration, and temperature extremes.

The light emitted by the laser or LED passes through the pigtail and connector into the fiber. The length of the fiber depends on the specific application and ranges from a few feet to several hundred miles. At the far end of the fiber, the light passes through another connector and pigtail fiber. This time, however, the pigtail fiber is glued to a photodetector rather than to a source. The photodetector is the heart of the receiver module. It is a semiconductor device that "demodulates" an optical signal by generating a current proportional to the intensity of the optical radiation, thereby converting the variations in optical intensity into an electrical signal that is a replica of the orginal signal input to the transmitter at the other end of the link.[3]

4.0 HISTORY

I earlier described fiber optics as a new technology, but glass fibers were made by the Egyptians over 5,000 years ago. The Egyptian fibers, however, were used as jewelry and decoration, and there is no record of their being used to transmit light.

The first recorded scientific investigation of the use of a transparent conductor to guide light is credited to John Tyndall, an English philosopher. In 1870, he demonstrated that light can be guided within a jet of water. Ten years later, Alexander Graham Bell demonstrated that light can be used as a communication medium. His photophone used unguided modulated sunlight to transmit speech about 700 feet (213 m).[4]

In 1910, researchers performed theoretical investigations of the properties of dielectric waveguides, including glass rods. These and other theoretical and experimental investigations continued through the early part of the century.

In 1966, Charles Kao and George Hockham, two scientists working at ITT Standard Telecommunications Laboratories in Harlow, England, proposed the idea of using glass fiber as a waveguide for optical communication. They estimated that the attenuation of the glass fiber would have to be less than 20 dB/km for the fiber to be competitive with copper wire. The attenuation of available fibers was typically 500 dB/km to 1000 dB/km. Making the advancement necessary in materials technology to achieve such a drastic reduction in attenuation appeared hopelessly optimistic, yet it took only four years.

In 1970, Corning Glass Works produced the first 20 dB/km glass fiber. By 1972, losses were down to 4 dB/km in laboratory samples. Today, commercial fibers are available with attenuation in the range of 0.2 to 0.5 dB/km.

The rapid advancement made in optical fiber technology during the '60s and '70s was matched by equally impressive advancements in semiconductor devices, such as LEDs, lasers, and optical detectors. During the '70s, the military and telephone industry provided the impetus for marrying optical fibers and semiconductors into highly efficient communication systems.

For telephone companies, fiber optics offers long-distance, high-capacity transmission particularly suited to transmitting digital data, video, and voice. The dielectric properties of fibers reduce electromagnetically induced problems, and the small size permits efficient use of crowded conduits or cable ways. For the military, fiber's light weight, survivability, and security are additional reasons for using fiber optics.

In 1977, the three major U.S. telephone companies--GTE, AT&T, and ITT--installed the first fiber optic links in systems used by residential and business customers. Today, there are tens of thousands of kilometers of optical cables installed in the United States. See Figure 4. AT&T expects to produce about 10 million kilometers of optical fibers in 1986.

5.0 COMMERCIAL FIBER OPTIC SYSTEMS

Telephone service over optical cable is already available in most of the East, South, and Midwest; in parts of the West and Southwest; and in the San Francisco-Los Angeles corridor. Cable has been installed in unused oil pipelines and in trenches along railroad, highway, and public utility rights-of-way. In Canada, construction has begun on regional fiber optic communication systems, and plans are under way for a transcontinental system. In Japan, a nationwide supertrunk is in service.

Underwater optical cable systems range from a system operating in Lake Washington in the Seattle area to those being constructed or planned to span the Atlantic and Pacific. The 4154-mile (6,684-km) Eighth Transatlantic Telephone Cable, TAT-8, is scheduled to be on-line by 1988. The 75-mile (120-km) prototype has been laid and will have its first real-world test this year when commercial service begins in the Canary Islands. The second and third transatlantic fiber optic systems, Market Link and TransAtlantic Video Submarine Cable System (TAV-1), are scheduled to begin service in 1989. Both systems are private.

The Federal Communications Commission has approved plans for a Pacific fiber optic network, the 7,175-mile (11,545-km) Transpac-3. The system is scheduled to link the U.S. mainland and Hawaii with Japan and Guam. Service may begin by the end of 1988. After completion of the supertrunk, cable will be laid

from Japan to Korea to Hong Kong to the Philippines and back to Guam, with a branch from the Philippines to Taiwan. Australia plans to install a cable between it, Indonesia, and Singapore.

It is clear that fiber optics is the transmission medium of choice for long-haul communication links. A somewhat more controversial use of optical fibers in terms of cost effectiveness is in LANs, or as we sometimes call them in the Navy, "data transfer networks." With the increasing use of data communication and accelerating communication speeds, fiber optic technology can be cost effective in many LAN applications. Fiber optic LANs have been installed in office buildings, supermarkets, universities, cable TV systems, Disney World, and aboard commercial ships.

Other commercial uses of optical fibers include flexible endoscopes that are used to examine internal body cavities. One company has combined fiber optics with solid-state sensors to form a camera small enough to be inserted into human veins. Industrial versions of the endoscopes are called "fiberscopes" or "borescopes" and are used to inspect jet engines, heat exchangers, critical piping, and valves.

Optical fibers are also being used for various undersea, underground, and space applications. Offshore oil drillers use fiber cable to carry commands from the drilling platform to devices on the ocean floor. Fiber optic sensors are lowered into oil wells to measure temperature and pressure. In space, fiber links and sensors are used on satellites, and NASA plans to use fiber on the space station. NASA has over 40 programs using fiber optics.

6.0 CONCLUSION

Fiber optic technology is at hand, but we have barely scratched the surface for potential Navy applications. To get on with the job of using fiber optic technology, the Navy has established a dedicated fiber optics program office. CNO has designated OP-03 to be the sponsor for fiber optics standard and specification development in the Navy. NAVSEA has been tasked with coordinating the Navy's fiber optics standardization development program and with expediting the acceptance and use of fiber optics in the Navy.

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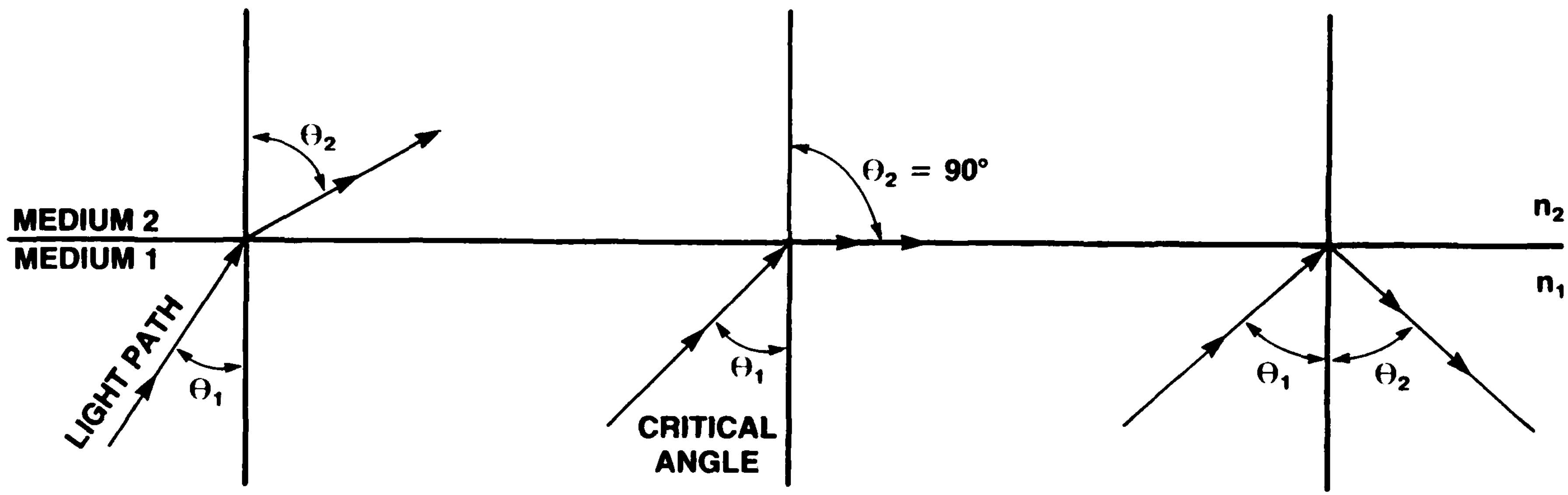
REFRACTION AND REFLECTION AT INTERFACE BETWEEN TWO MEDIA

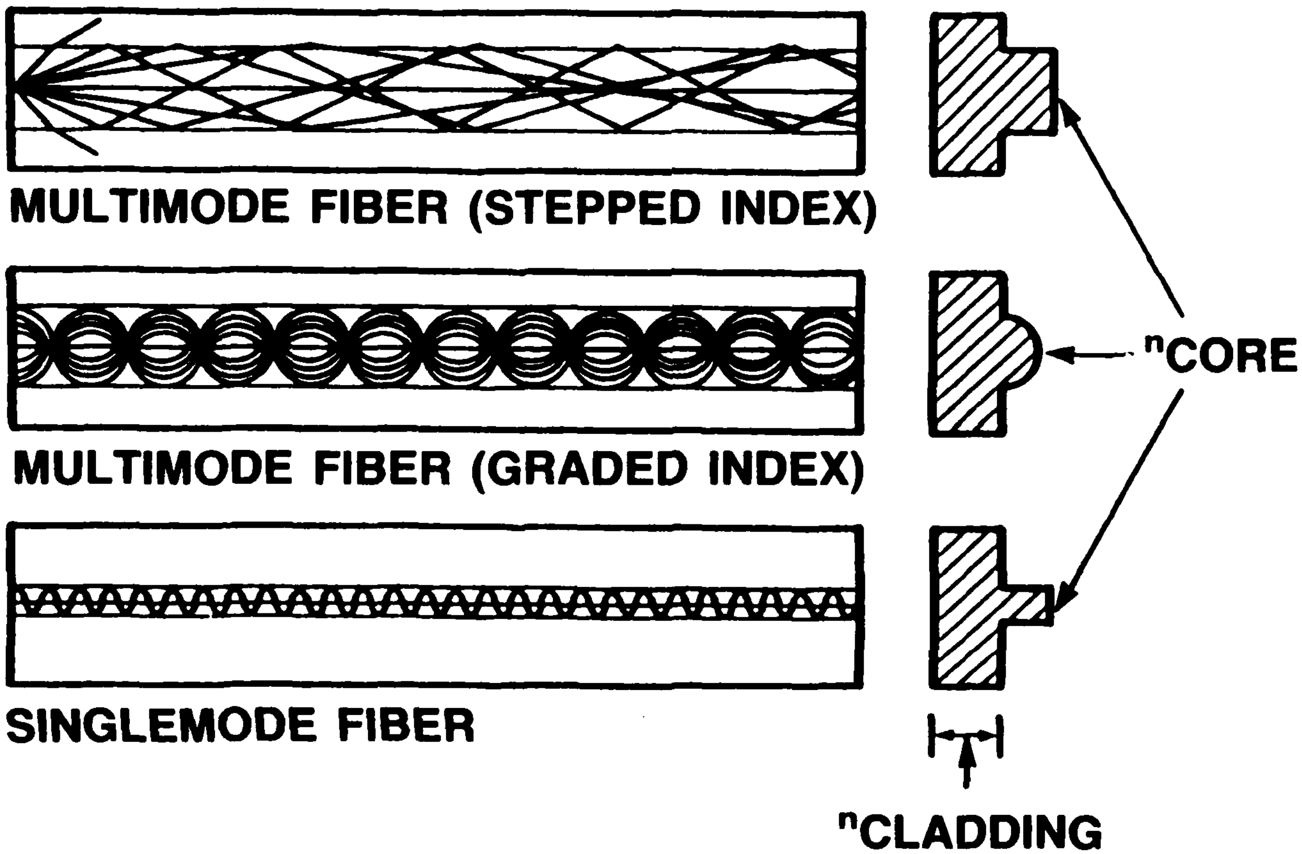


REFRACTION
$n_1 \mathrm{Sin}\Theta_1 = n_2 \mathrm{Sin}\Theta_2$

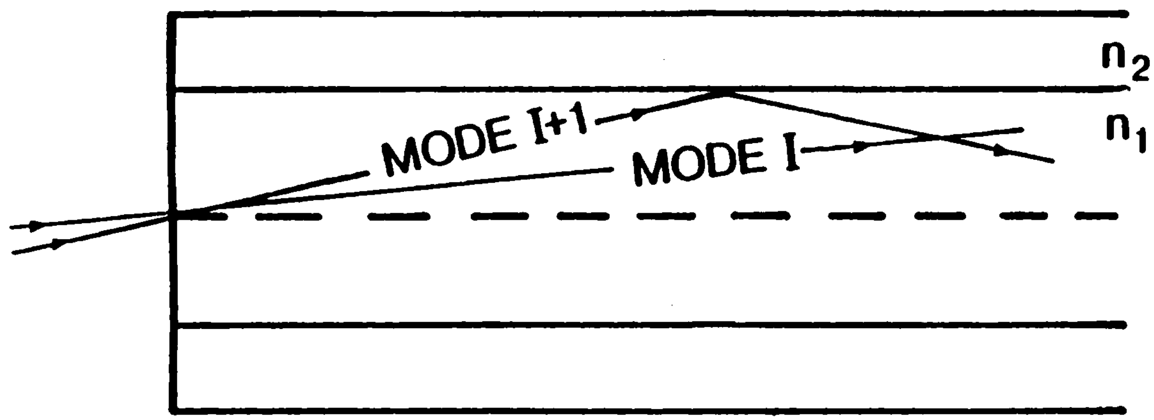
CRITICAL ANGLE
$\mathrm{Sin}\Theta_1 = n_2/n_1$

REFLECTION
$\Theta_1 = \Theta_2$

REFRACTIVE INDEX PROFILES AND MODE STRUCTURE



RELATION BETWEEN RAYS AND ALLOWED MODES



- MODE NUMBER PROPORTIONAL TO RAY ANGLE
- LOW ORDER MODES CORRESPOND TO LOW ANGLE RAYS
- HIGH ORDER MODES CORRESPOND TO HIGH ANGLE RAYS
- EACH MODE HAS CHARACTERISTIC VELOCITY
  - LOWER ORDER ⟶ LOWER VELOCITY

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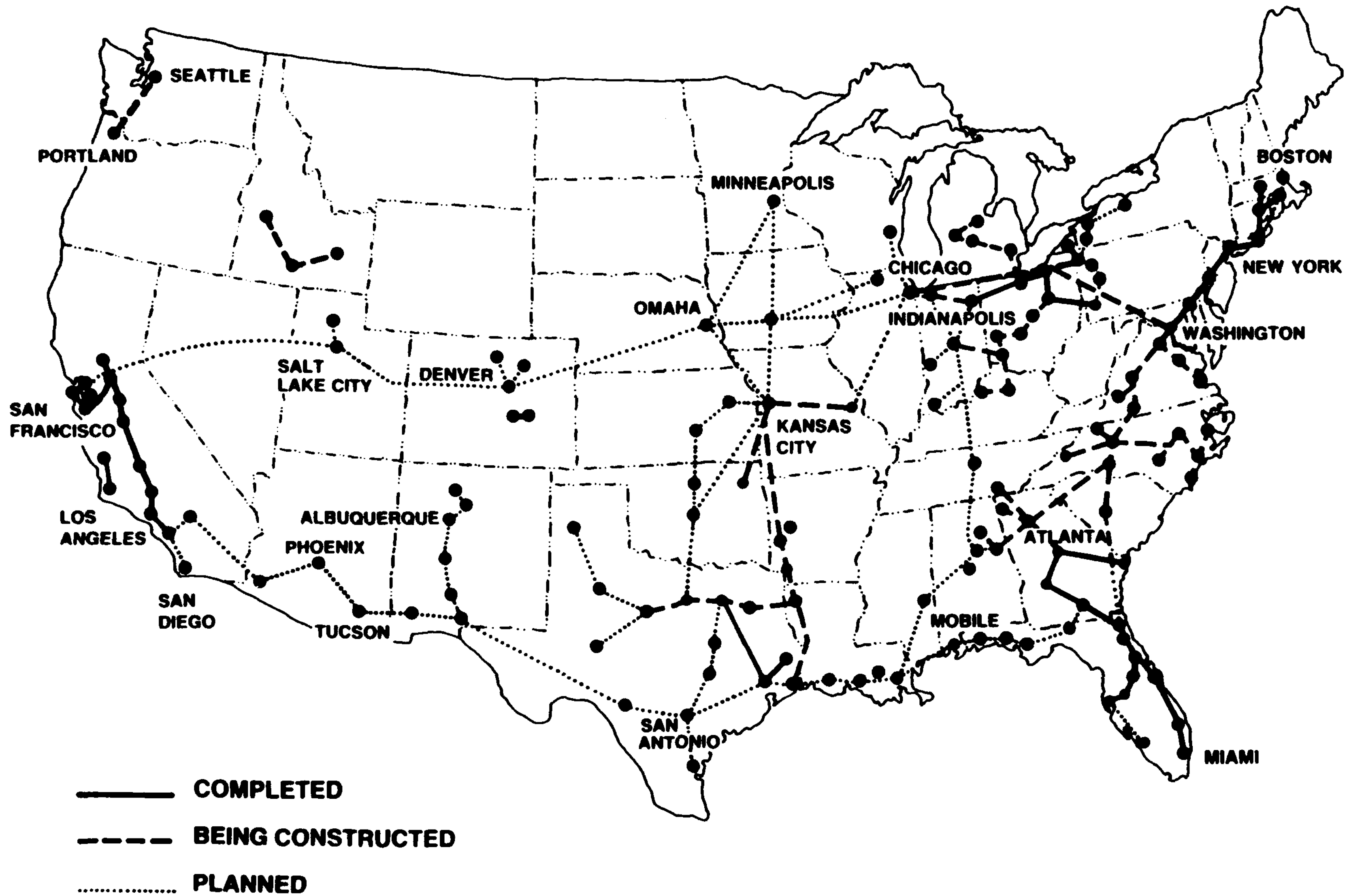
FIBER OPTIC TELECOMMUNICATIONS NETWORKS



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